Arnold Schwarzenegger
Governor

FIFTY-TWO YEARS OF "PINEAPPLE-EXPRESS" STORMS ACROSS THE WEST COAST OF NORTH AMERICA

PIER Project Report

Prepared For:
California Energy Commission
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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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- Energy Innovations Small Grant Program
- Energy-Related Environmental Research
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- Renewable Energy Technologies

The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

The work described in this report was conducted under the Preliminary Climatic Data Collection, Analyses, and Modeling contract, Contract Number 500-02-04, Work Authorization MR-004, by the Michael Dettinger of the U.S. Geological Survey, Scripps Institution of Oceanography.

For more information on the PIER Program, please visit the Energy Commission's Web site www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-4628.

Abstract

Pineapple-express circulations yield warm-wet storms along the west coast of North America, and are known for the floods that they can generate. This study analyzed daily water-vapor transport pathways from the NCEP Reanalysis to identify the occurrence of these circulations throughout the 52-year period from 1948 to1999, independently of whether the days were actually warm or wet on the West Coast. This approach identified 206 days on which large-scale atmospheric circulations were symptomatic of the pineapple-express condition. These days all occurred between October and April, most often in January and February. The water-vapor transports crossed the West Coast anywhere from 32ºN to 52ºN, with a modest maximum near 45ºN. The circulations have been most pronounced during winters when the PDO is in its positive, El Niño-like phase with ENSO in neutral or near-neutral conditions. The circulations yield storms over the West Coast states (and into Nevada and Idaho) and warm conditions over most of the western states. In the Sierra Nevada during winter, the storms average about twice as much precipitation as other, non-pineapple-express storms, yield warmer minimum temperatures, and produce daily increases in streamflow that are an order of magnitude larger than those from other types of storms.

1. Background and Motivation

Among the many configurations that winter storms over the northeastern Pacific Ocean can take, some of the most feared are the so-called "pineapple-express" storms. These storms are characterized by their tendency to draw warm, wet air from the tropics near Hawaii (hence their name) and to deliver it in violent, unusually warm and unusually wet storms on the west coast of North America. Winter flooding of West Coast rivers has often been attributed to these storms (e.g., http://www.usatoday.com/weather/ wpinappl.htm). The risks associated with these storms could more readily be quantified and predicted if a multi-decade historical chronology of when and where the storms occurred, and of the large-scale atmospheric circulation conditions that have supported them, was available.

The details of such a chronology will depend on how the pineapple-express storms are defined and recognized. One approach would be to count and catalog the number of especially warm-wet winter storms at West Coast weather stations. However, this approach threatens to become circular if the characteristics of the storms associated with this particular subset (of storms) is the primary interest; that is, one finds that—by definition—the storms identified are just as warm and wet as necessary to be counted as warm and wet. This circularity can hamper assessments of the risks and climatology of the storms.

Alternatively, pineapple-express storms are readily recognizable in even the simplest weather-satellite imagery (e.g., top panels of Figures. 1 and 2, showing infrared imagery from the Geostationary Operational Environmental Satellite [GOES]) as distinctive jet-like cloud paths (white streaks) connecting landfalling storms on the West Coast to the tropics near Hawaii. More precise identifications and characterizations of the storms have been made using Special Sensor Microwave Imager (SSMI) vapor- and cloud-microphysical retrievals from various satellites (Ralph et al. 2004). However, these satellite approaches are only possible during the period with adequate satellite imagery, which in practice limits this approach to storms during the past two to three decades.

A third alternative, undertaken here, is to develop the chronology based on the particular atmospheric wind and moisture patterns that create pineapple-express storms, identified from the large-scale atmospheric features recorded in daily (digital) records of Northern Hemispheric weather. This approach can be used to identify the storms since the (practical) beginning of continuous observations of these three-dimensional atmospheric structures in the late 1940s. In the present study, the central role of water-vapor transport from the tropics near Hawaii to the West Coast, where the storms have their greatest societal impact, is recognized and provides motivation for focusing on the daily large-scale, vertically integrated water-vapor transport paths as the feature that identifies pineapple-express storms. By identifying the pineapple-express events from the regional northeast Pacific configuration of vapor transports and atmospheric circulations that cause them, rather than just the warmth and wetness of selected storms at West Coast locations, both full-blown pineapple-express storms and "near misses" can be recognized and studied. Using daily weather fields allows the storms that occurred several decades before the earliest available weather-satellite images (ca. 1993, from online sources) to be recognized. This approach is limited, though, by the coarseness of the weather fields that are available in consistent form during the past 50 years. Ralph et al. (2004) have shown, by use of a variety of satellite, airborne, and surface-based instruments, that pineapple-express storms are examples of transient "atmospheric rivers" (Zhu and Newell, 1998) and that these atmospheric rivers are typically only a few hundred kilometers wide. The rivers form from the intense mid and lower tropospheric winds that conduct heat and water vapor poleward in the warm sectors of eastward-moving, midlatitude low-pressure cyclones (Figures 1, 2, and 3). The narrow structure, and the intensity of water-vapor transport in the narrow pathways, is in keeping with Zhu and Newall's (1998) conclusions that atmospheric rivers conduct more than 90% of the overall poleward water-vapor transports in the extratropics, while covering less than 10% of total hemispheric circumference on average. This narrow structure is poorly resolved in available historical weather fields, which are constructed on 2.5º x 2.5º latitude-longitude grids and which are based mostly on observations from outside the northeastern Pacific. Thus the largest (and widest) pineapple-express "jets" are most likely to be identified by the methods employed here.

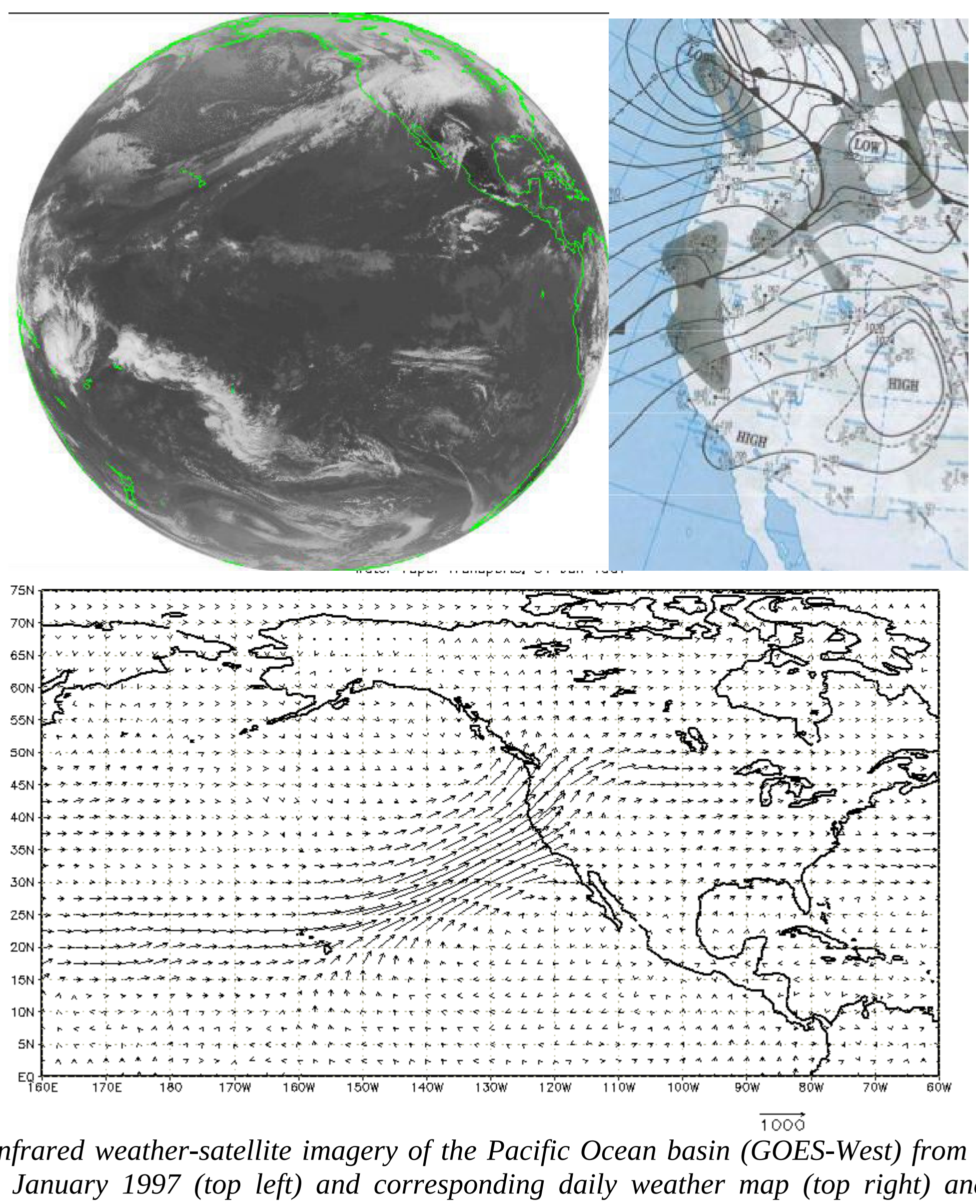


Figure 1. Infrared weather-satellite imagery of the Pacific Ocean basin (GOES-West) from 1800 hours GMT on 1 January 1997 (top left) and corresponding daily weather map (top right) and vertically integrated water-vapor transport directions and relative rates (bottom); arrow at bottom indicates length of a 1000 kg/m/s transport.

Despite this limitation, the chronology of days with high water-vapor transports connecting the tropics to the West Coast developed here identifies many of the well-known pineapple-express storms in the past five decades. This method (discussed in Section 2) provides a historical record for analyzing the geography, seasonality, and interannual variability of when and where these storms make landfall on the West Coast (discussed in Section 3) and for assessing the meteorological and hydrological conditions engendered by the storms in the western states and, as an example, in the central Sierra Nevada (discussed in Section 4). These analyses are first steps toward risk assessments of Californian pineapple-express storms from a longer-term perspective than has been possible by other methods. The circulation-based approach eventually may be extended to predict changes in the frequency and severity of pineapple-express storms in climate-model projections of twenty-first century climate changes in response to increasing greenhouse-gas concentrations in the atmosphere.

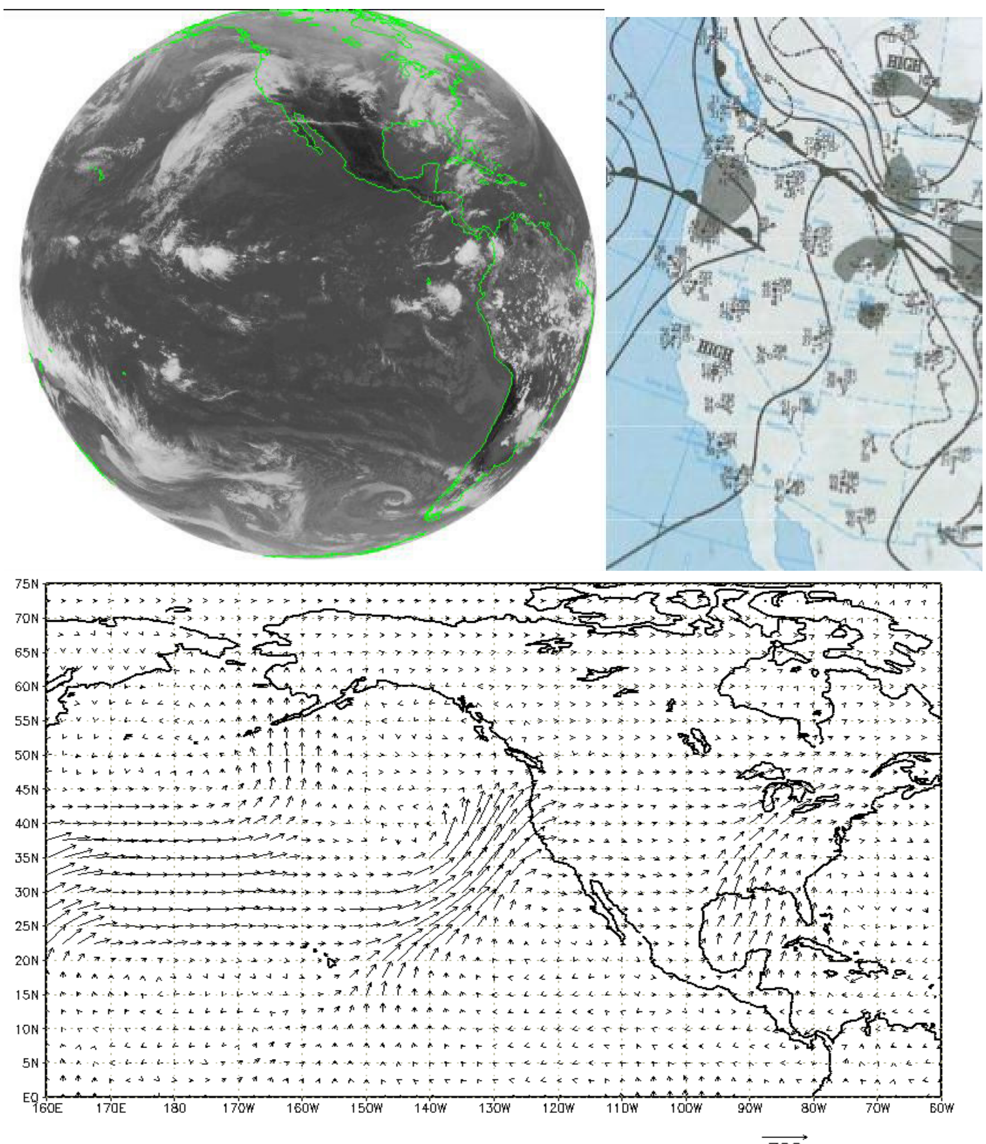


Figure 2. Same as Figure 1, except for 16 March 1993, the earliest available example of a pineapple-express storm captured in the satellite imagery provided by the online National Climatic Data Center Historical GOES Browse Server (http://cdo.ncdc.noaa.gov/GOESBrowser/goesbrowser).

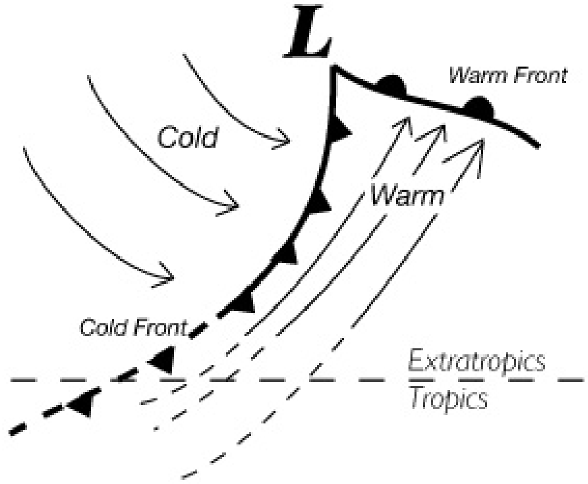


Figure 3. Much idealized structure of a midlatitude low-pressure cycle, showing low-pressure center ("L"), wind directions, fronts, and air temperatures (after Carlson 1991). Southwesterly winds in the warm sector conduct much heat and water vapor into storm and, if the winds are intense enough and reach far enough south, the resulting jet can feed a pineapple-express storm on the West Coast; cold fronts and winds do not always come from as far south as the dashed curves indicate.

2. Method of Detection

This study has developed a list of 206 possible pineapple-express storms from among the 18,993 days between 1948 and 1999 (Table 1). Candidate storms were identified by considering every day's weather conditions (regardless of season) and finding all days during which intense water-vapor transport pathways formed a concentrated jet that extended continuously back from the West Coast to the tropical atmosphere over the central to eastern Pacific. Vertically integrated vapor-transport vectors were calculated from geopotential height, wind, air-temperature, and water-vapor mixing-ratio fields—from the National Centers for Environmental Prediction (NCEP) Reanalysis I (Kalnay et al. 1996 and updates thereto). The products $q*u*dp/g$ and $q*v*dp/g$ were vertically integrated from the Earth's surface to the 300-hPa pressure level at each grid point, at six-hour intervals, where q is water-vapor mixing ratio, u is the west-east wind, v is south-north wind, dp is the differential pressure (vertical distance measured in terms of atmospheric pressure), and g is gravitational acceleration. (Weighting by dp/g ensures that the vapor transports are weighted by the mass of water at each level.) These six-hourly values were summed to form daily eastward water-vapor transport component, $\langle qu \rangle$, and northward component, $\langle qv \rangle$, of atmospheric water-vapor transport at each grid cell. The resulting vectors represent daily rates and directions of overall vapor transport above each grid point (e.g., bottom panels of Figures 1 and 2). Daily, vertically integrated vapor transports were thus calculated for every 2.5º grid cell in the NCEP Reanalysis fields for the entire period from 1948–1999.

To identify pineapple-express circulations, back trajectories of the transport paths originating along 120ºW longitude at each latitude from 32.5ºN to 52.5ºN were categorized by the intensity of vapor transport and whether or not the transport pathways form direct and continuous connections to regions over the northern part of the tropical Pacific (between 20º to 25ºN latitude). Transport pathways were considered to be continuous if the transport direction into each grid cell along the trajectory was from somewhere in the southwest quadrant of the preceding grid cell on the trajectory, until the tropical Pacific east of 170ºW longitude was reached. Only days with at least one such pathway along which vapor transport averaged 500 kg/m/s was present were identified as possible pineapple-express circulations in the present study; other intense events that were not well characterized by the relatively coarse grid of the NCEP Reanalysis fields and other events that were not this intense were not included in the population of days identified here. Notice that the detection method employed here uses no information about the storm conditions (or lack thereof) at West Coast weather stations and thus allows us to address the occurrence of both major pineapple-express storms and "near misses."

The 206 days between 1948 and 1999 that were identified by this method are listed in Table 1. Among the days identified as possible pineapple-express circulations were well-known pineapple-express storms, including the New Years 1997 (Figure 1), Presidents Day 1986, and pre-Christmas 1955 storms, each of which produced heavy flooding in parts of California. Many other events in the more recent part of the list were corroborated by inspection of the GOES satellite imagery. Still more events are identified by this method during the pre-satellite period.

3. Seasonal, Geographic, and Interannual Distributions

Pineapple-express circulations large enough to be identified here occur, on average, four days per year. The pineapple-express circulations have all occurred between October and April, as indicated by the histogram in Figure 4. Most pineapple-express storms occur in January and February. During these months, on average, the jet stream and storm tracks over the North Pacific are in their southernmost positions (curve in Figure 4). When the storm track is in this southern position, the southern ends of midlatitude storm fronts are more likely to reach into the tropics to draw the warm, moist air that characterizes the storms northeastward to the west coast of North America (Figure 3).

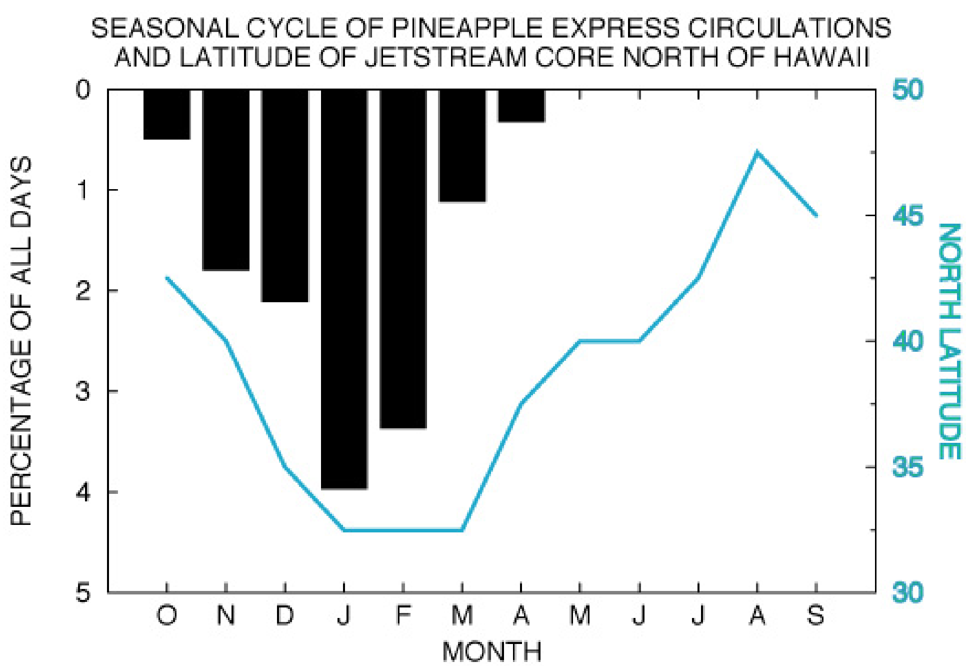


Figure 4. Mean seasonal cycles of the timing of pineapple-express circulations (bars) and the latitude of the jet stream core (maximum wind speeds at 250 hectopascals (hPa) pressure levels) north of Hawaii (curve); notice that the timing histogram has been reversed for comparison to the latitude curve.

Table 1. Days identified as having pineapple-express circulations, 1948–1999, with transport rates as average vertically integrated water-vapor transport rate along the back trajectory with largest average transports, path length as the number of 2.5º grid cells traversed along the back trajectory to reach either southern terminus or 20ºN (whichever was reached first), West-Coast crossing as the longitude at which the trajectory with largest transport rates crosses 120ºW, and southern limit as the southernmost latitude that connects with the southwesterly back trajectory or 20ºN (whichever was reached first). Southern limit is asterisked if visual inspection of the transport vectors for a day indicates a deep tropical water-vapor source; other days typically draw most of their vapor from between 20º and 30.5ºN.

YEAR	MONTH	DAY	TRANPORT RATE	PATH LENGTH	WEST COAST CROSSING	SOUTHERN LIMIT
1949	10	31	514 kg/m/s	15 cells	52.5ºN	25.0ºN
1950	11	1	545	21	40.0	22.5
1950	11	20	549	10	40.0	20.0
1950	12	3	642	10	42.5	20.0
1950	12	5	631	12	47.5	20.0 *
1950	12	6	584	12	47.5	20.0
1951	12	27	544	11	40.0	25.0 *
1951	12	28	656	9	32.5	20.0
1952	1	23	510	9	40.0	20.0
1952	12	12	562	14	50.0	20.0
1953	1	1	518	15	40.0	20.0
1953	1	8	714	12	45.0	22.5
1953	1	9	683	10	42.5	20.0
1953	12	19	610	12	40.0	22.5
1954	3	8	759	8	37.5	20.0 *
1954	11	4	523	13	52.5	22.5
1954	11	20	647	15	52.5	20.0
1954	11	21	530	13	50.0	22.5
1955	12	18	515	9	40.0	20.0
1955	12	19	632	8	37.5	20.0
1955	12	21	878	12	47.5	20.0 *
1956	1	14	923	14	37.5	20.0
1956	1	19	553	21	42.5	25.0 *

YEAR	MONTH	DAY	TRANPORT RATE	PATH LENGTH	WEST COAST CROSSING	SOUTHERN LIMIT
1957	1	12	513	6	32.5	20.0
1957	2	22	530	12	45.0	20.0
1957	2	24	562	10	40.0	20.0 *
1957	2	25	672	11	45.0	20.0*
1957	2	26	585	10	40.0	20.0 *
1958	1	13	505	17	47.5	20.0
1958	2	20	513	17	50.0	25.0
1958	12	1	529	11	47.5	22.5
1958	12	2	624	13	50.0	25.0
1959	2	15	804	15	45.0	22.5 *
1960	1	28	573	11	45.0	20.0
1962	2	9	585	8	35.0	25.0
1962	3	5	505	6	32.5	20.0
1963	1	30	794	9	40.0	20.0
1963	1	31	884	9	40.0	20.0
1963	2	1	830	12	35.0	20.0
1963	2	2	735	11	42.5	20.0
1963	2	3	633	13	50.0	20.0
1963	3	27	570	7	35.0	20.0
1963	12	22	527	12	52.5	25.0
1964	12	21	602	11	45.0	20.0
1964	12	22	988	14	42.5	20.0
1965	11	16	590	6	32.5	20.0

YEAR	MONTH	DAY	TRANPORT RATE	PATH LENGTH	WEST COAST CROSSING	SOUTHERN LIMIT
1965	11	22	570	6	32.5	20.0
1967	2	2	529	20	47.5	22.5
1967	3	16	539	7	35.0	20.0
1968	1	14	572	9	40.0	20.0
1968	1	18	596	13	50.0	20.0
1968	1	19	502	13	50.0	20.0
1968	1	20	514	15	52.5	20.0
1968	2	17	672	12	45.0	20.0
1968	2	20	645	16	40.0	20.0
1968	11	7	572	17	45.0	20.0
1968	11	8	560	18	45.0	20.0
1969	1	11	518	10	35.0	20.0
1969	1	12	602	7	35.0	20.0
1969	1	18	623	8	32.5	20.0
1969	1	24	562	9	32.5	20.0
1969	1	25	623	6	32.5	20.0
1969	12	20	548	11	45.0	25.0
1970	1	14	623	16	35.0	20.0
1970	1	15	624	14	37.5	25.0
1970	1	17	503	21	37.5	22.5
1970	1	18	559	21	50.0	25.0
1970	2	15	525	11	45.0	20.0
1970	11	22	593	11	42.5	20.0
1970	11	23	610	11	45.0	20.0
1970	11	24	508	11	42.5	20.0
1971	1	15	607	11	45.0	20.0
1971	1	16	671	13	50.0	20.0
1971	1	17	767	13	42.5	20.0
1971	1	18	576	13	42.5	20.0
1971	2	10	616	20	45.0	25.0
1971	3	22	531	14	42.5	20.0
1972	10	31	525	16	52.5	20.0
1972	12	16	592	10	42.5	20.0
1972	12	19	539	16	45.0	25.0
1973	11	9	537	11	45.0	25.0
1973	11	11	528	9	37.5	25.0
1974	1	13	577	21	40.0	25.0
1974	1	15	928	13	45.0	25.0
1974	1	16	697	21	37.5	25.0
1977	1	17	507	15	52.5	20.0
1977	2	10	515	20	47.5	25.0
1977	11	23	556	16	42.5	20.0
1977	11	24	637	15	42.5	20.0
1977	11	25	509	11	47.5	25.0
1977	12	12	585	19	42.5	20.0
1977	12	21	553	6	32.5	20.0 *
1977	12	25	549	6	32.5	20.0 *
1977	12	26	582	6	32.5	20.0 *
1978	11	27	526	19	45.0	22.5
1979	1	9	514	14	37.5	20.0
1979	1	10	623	14	40.0	20.0
1979	2	12	794	13	50.0	20.0
1979	2	13	599	9	37.5	22.5
1979	4	25	605	7	32.5	20.0
1980	1	11	1079	15	32.5	20.0
1980	2	1	521	12	47.5	20.0
1980	2	15	769	6	32.5	20.0 *
1980	11	3	564	14	50.0	25.0
1980	12	10	567	21	52.5	25.0
1980	12	24	610	12	47.5	20.0
1980	12	25	762	11	47.5	22.5
1981	1	17	620	13	35.0	20.0
1981	2	12	605	12	45.0	20.0
1981	2	13	574	9	42.5	22.5
1981	2	14	703	20	45.0	20.0 *
1981	2	15	735	17	47.5	20.0

YEAR	MONTH	DAY	TRANPORT RATE	PATH LENGTH	WEST COAST CROSSING	SOUTHERN LIMIT
1981	4	27	512	19	47.5	22.5 *
1982	1	7	542	21	50.0	20.0
1982	2	12	658	13	32.5	20.0
1982	2	13	705	12	47.5	20.0 *
1982	2	18	564	12	47.5	25.0
1982	4	9	504	10	35.0	25.0
1982	4	10	811	7	35.0	20.0
1982	4	11	568	6	32.5	20.0
1982	10	22	513	7	37.5	22.5
1982	10	28	509	12	50.0	25.0
1983	1	6	635	21	42.5	25.0
1983	1	25	520	10	42.5	20.0
1983	2	10	656	14	42.5	25.0
1983	2	17	599	13	47.5	25.0
1983	2	28	547	8	35.0	25.0
1983	3	1	571	7	32.5	25.0
1983	3	8	546	11	45.0	20.0
1983	12	23	608	11	37.5	20.0 *
1983	12	24	660	10	42.5	20.0 *
1983	12	31	546	20	47.5	25.0
1984	1	1	523	15	52.5	20.0
1984	1	4	574	14	47.5	22.5
1986	1	18	695	13	50.0	20.0
1986	1	29	559	6	32.5	20.0
1986	2	13	547	8	37.5	20.0
1986	2	14	3417	6	35.0	22.5
1986	2	16	603	13	35.0	20.0 *
1986	2	17	705	10	37.5	20.0
1986	2	18	641	9	35.0	20.0
1986	2	22	650	19	45.0	22.5
1986	2	23	625	16	47.5	20.0
1987	1	10	582	12	52.5	25.0
1987	3	4	656	14	52.5	20.0 *

YEAR	MONTH	DAY	TRANPORT RATE	PATH LENGTH	WEST COAST CROSSING	SOUTHERN LIMIT
1988	1	3	577	9	40.0	20.0
1988	1	14	520	11	47.5	22.5
1988	10	15	608	16	45.0	25.0
1989	3	5	555	10	40.0	22.5
1990	2	20	523	14	50.0	20.0 *
1990	11	9	591	19	45.0	22.5
1990	11	12	509	12	50.0	22.5 *
1991	1	3	2573	8	40.0	22.5
1991	3	3	618	9	40.0	20.0
1992	1	23	557	15	50.0	25.0
1992	1	29	582	14	52.5	20.0
1992	1	30	544	12	47.5	20.0
1992	11	3	538	14	52.5	25.0
1993	1	5	566	6	32.5	20.0 *
1993	3	16	516	10	40.0	20.0 *
1995	1	28	663	21	42.5	25.0
1995	1	30	590	12	47.5	20.0
1995	1	31	623	16	50.0	25.0
1995	2	17	590	21	50.0	25.0
1995	2	18	609	15	52.5	20.0
1995	2	19	507	13	47.5	20.0
1995	3	9	575	12	37.5	22.5
1995	3	10	629	8	35.0	25.0
1995	12	9	592	21	47.5	25.0
1995	12	29	721	19	40.0	20.0
1996	1	10	590	18	50.0	22.5
1996	1	30	539	8	32.5	22.5
1996	2	2	607	11	32.5	20.0 *
1996	2	3	584	9	40.0	20.0
1996	2	5	659	17	50.0	20.0
1996	2	6	631	15	45.0	20.0
1996	11	8	514	20	50.0	20.0
1996	11	17	575	16	37.5	20.0 *

YEAR	MONTH	DAY	TRANPORT RATE	PATH LENGTH	WEST COAST CROSSING	SOUTHERN LIMIT
1996	11	19	633	9	40.0	20.0
1996	12	9	506	6	32.5	25.0
1996	12	28	642	14	40.0	25.0
1996	12	29	761	10	42.5	20.0
1997	1	1	883	10	42.5	20.0
1997	1	17	548	14	47.5	22.5
1997	1	24	502	9	35.0	20.0
1997	1	28	509	16	50.0	20.0
1997	1	29	822	15	52.5	20.0
1997	1	30	637	14	50.0	20.0
1997	3	19	516	11	45.0	22.5
1998	3	22	549	9	40.0	20.0

The pineapple-express jets most commonly cross the west coast with their centers near 45ºN (Table 1). Crossings are generally common, however, across the entire latitudinal range considered. The latitudes of these west coast crossings have not trended significantly during the past 50 years (Figure 5a), although large year-to-year variations are observed.

Substantial year-to-year variations also occur in both the number (Figure 5b) and intensities of the pineapple-express circulations. Historically, neither the number (not shown) nor the intensity of the pineapple-express circulations identified here has correlated directly with El Niño-Southern Oscillation (ENSO) (Allan et al. 1996) status ($r = +0.10$, $p \sim 0.3$; Figure 6a). Still, every El Niño winter has yielded at least one pineapple-express circulation; in contrast, four of the nine La Niña winters considered here had no pineapple-express days. The circulations are more pronounced, on average, during the positive, El Niño-like phase of the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997), mostly because the four or five winters with most vigorous pineapple-express transports have occurred under positive PDO conditions (Figure 6b), when the westerlies and storm tracks across the North Pacific tended to be farther south than in other decades. The correlation between the PDO index and

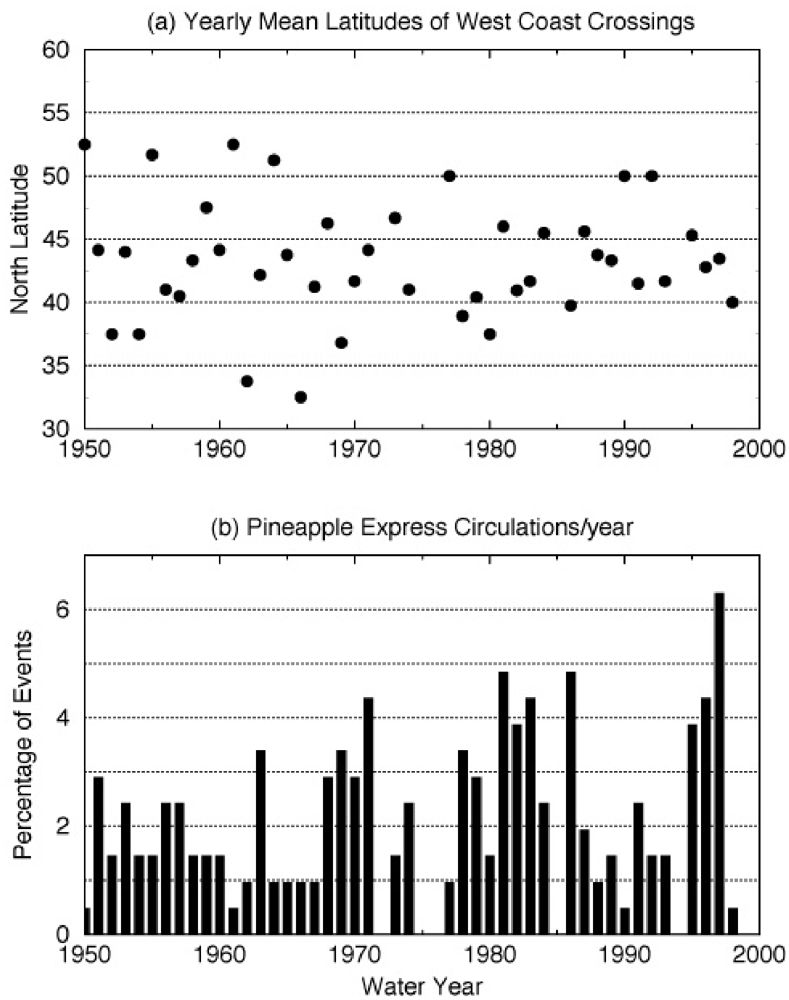
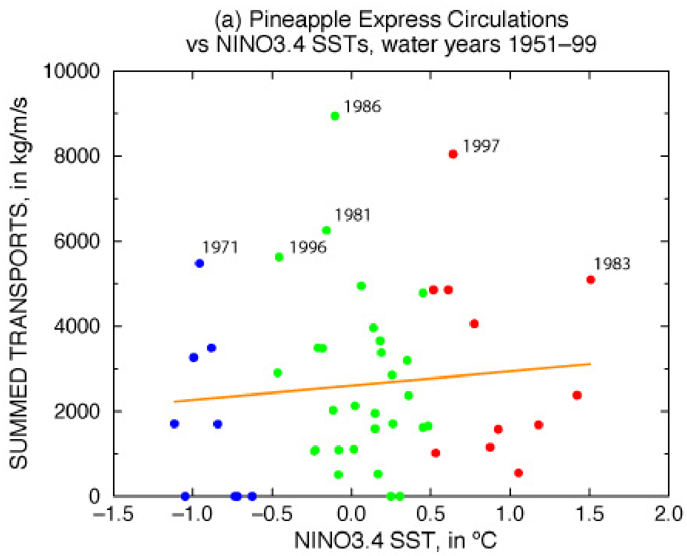


Figure 5. (a) Water-year (October–September) mean latitudes of West Coast (120ºW) crossing of the pineapple-express water-vapor transports, and (b) corresponding percentages of pineapple-express circulations per year (see Table 1).

winter-long sums of vapor transports (Table 1) has been +0.30 ($p < 0.005$) overall. The most vigorous pineapple-express seasons have been during neutral- or near-neutral ENSO years during the positive-PDO phases.

There are hints of a trend toward increasing numbers of the circulations per year during the 52 years studied here; the correlation between numbers of pineapple-express days and year = +0.18 ($p \sim 0.2$; Figure 4b). However, the NCEP Reanalysis fields (used in the classification) are less reliable prior to the satellite era (prior to 1979). Thus, the trend could easily reflect data availability and should not be trusted without more study.



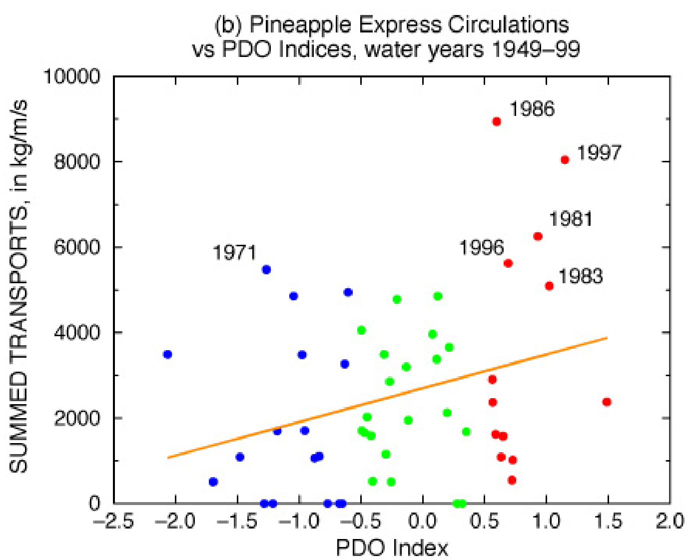


Figure 6. Relations (a) between the NINO3.4 sea-surface temperature (SST) index of the El Niño-Southern Oscillation and the sum of water-vapor transports (Table 1) by pineapple-express circulations, and (b) between the Pacific Decadal Oscillation (PDO) index and the circulations. Red dots indicate (a) El Niños and (b) El Niño-like PDO years; blue dots indicate (a) La Niñas and (b) La Niña-like PDO years; green dots are neutral years. Lines are regression fits.

4. Impacts on Western North America and the Sierra Nevada

The pineapple-express storms that result from the circulation patterns identified in the present analysis, on average, yield remarkably warm conditions in most of the western states (Figure 7a) and remarkably wet conditions in the West Coast states (and into Nevada and Idaho; Figure 7b). The sharp temperature contrasts between cool anomalies in western Canada and warm anomalies over the western United States are, in large part, a reflection of the cold and warm fronts shown in Figure 3.

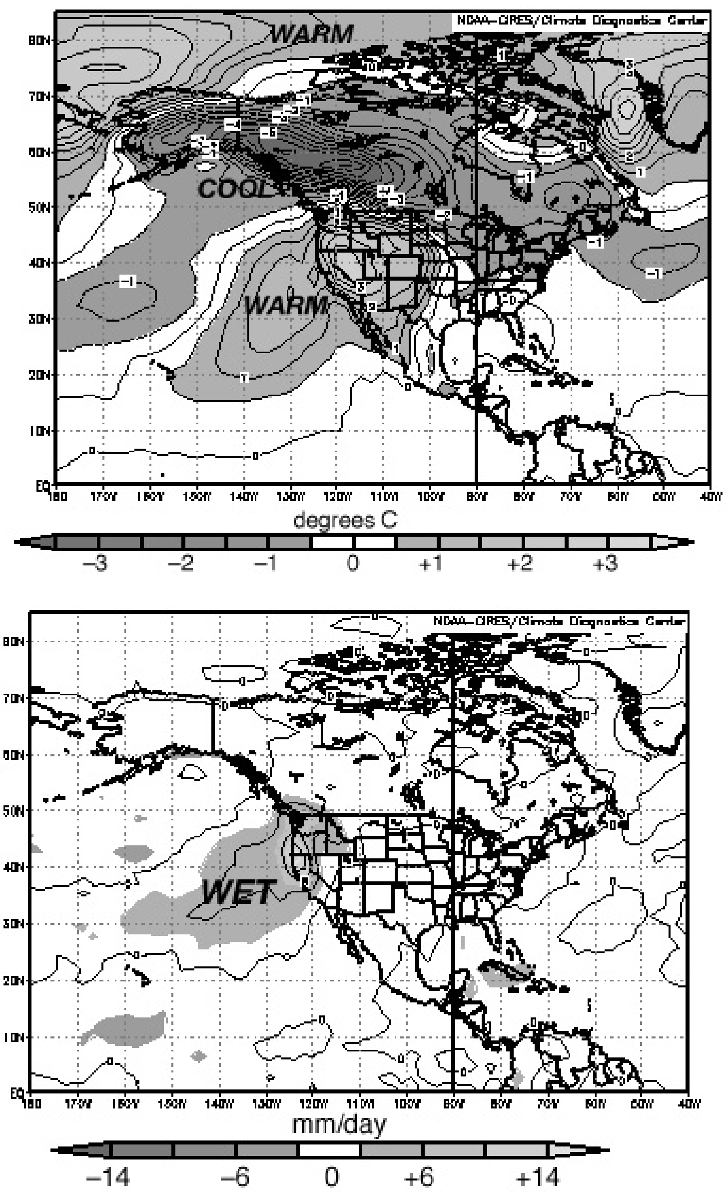


Figure 7. Average of deviation, on the 100 days with the most intense pineapple-express circulations of surface-air temperatures (top) and precipitation rates (bottom) from long-term mean. Graphics courtesy of the NOAA/Climate Diagnostics Center.

In the central Sierra Nevada at the long-term Yosemite Park Headquarters weather station, for example, the pineapple-express circulations have large effects on daily winter (December–February) minimum temperatures and precipitation rates at near all recurrence intervals, which is to say, across the full range of conditions observed during winters from 1948 to 1999. Daily minimum temperatures during pineapple-express circulations (not shown) are +5ºC warmer than minimum temperatures on other wet or dry days, at all recurrence intervals. Daily maximum temperatures during pineapple-express circulations, in contrast, are much less influenced. Maximum temperatures on the wettest pineapple-express days are not significantly different from maximum temperatures on other wet days, and maximum temperatures on the drier pineapple-express days are warmer but are similar to maximum temperatures on other dry days.

Precipitation on the winter days with pineapple-express circulations is about twice as likely to be wet at the Yosemite Park Headquarters station as other days, with 70% of pineapple-express days yielding precipitation, compared to only 37% of other days. On days when the pineapple-express circulations yield wet weather, precipitation totals are twice (e.g., median = 10 mm/day) as large as wet days with other circulations (5 mm/day), at all recurrence levels. Overall, pineapple-express storms contribute 7% of all winter precipitation, although they comprise only 3% of winter days. If only days with West Coast crossings (Table 1) of the pineapple-express jet near the latitude of Yosemite (about 37ºN) are considered, the median precipitation rate (15 mm/day) is three times as large on all wet winter days.

The hydrologic impact of these warm, wet storms can be profound. The warm, wet storms resulting from these circulations yield greatly enhanced increases in discharge, compared to other wet winter days. Cool winter storms typically deposit much of their precipitation as snow and deposit snow over large areas within the river basins. This snowfall does not contribute runoff to the rivers until the snow melts, often several months later, so that large precipitation totals need not translate into immediate flow increases. The warmth of the pineapple-express storms, by contrast, often results in rainfall onto larger parts of the basin than during other storms, so that larger areas of the basin contribute more runoff immediately. The storms also often deposit both rain and snow or rain at higher altitudes than have previous (cooler) storms, so that rain-on-snow melting events add to the already rich rainfall-runoff conditions. Furthermore, of 43 pineapple-express circulations that persisted more than one day, 33 were warmer in the Sierra Nevada after the first day; thus, opportunities for warm rains to fall on newly fallen snow may be common even within a single persistent pineapple-express storm.

The Merced River of Yosemite National Park in the Sierra Nevada responds significantly to pineapple-express storms. For example, the median change in daily discharge from the day before to the day after wintertime wet days in general is a negligible flow increase; the median response to a wet pineapple-express day is about a 2.6 cubic meter/second (92 cfs) flow increase (Figure 8). The more extreme flow increases associated with the pineapple-express storms are even larger than the corresponding flows on other days. For example, at the 5% recurrence interval (occurring only once in twenty of this kind of wet day), pineapple-express storms yield a 40-cubic meters/second (1400 cfs) flow increase, compared to 3.1-cubic meters/second (110 cfs) increases on other wet days. Thus, as expected, pineapple-express circulations can be major flood producers. Overall, flows during winter pineapple-express storms contribute about 7% of all December–February flows in the river in 3% of the days.

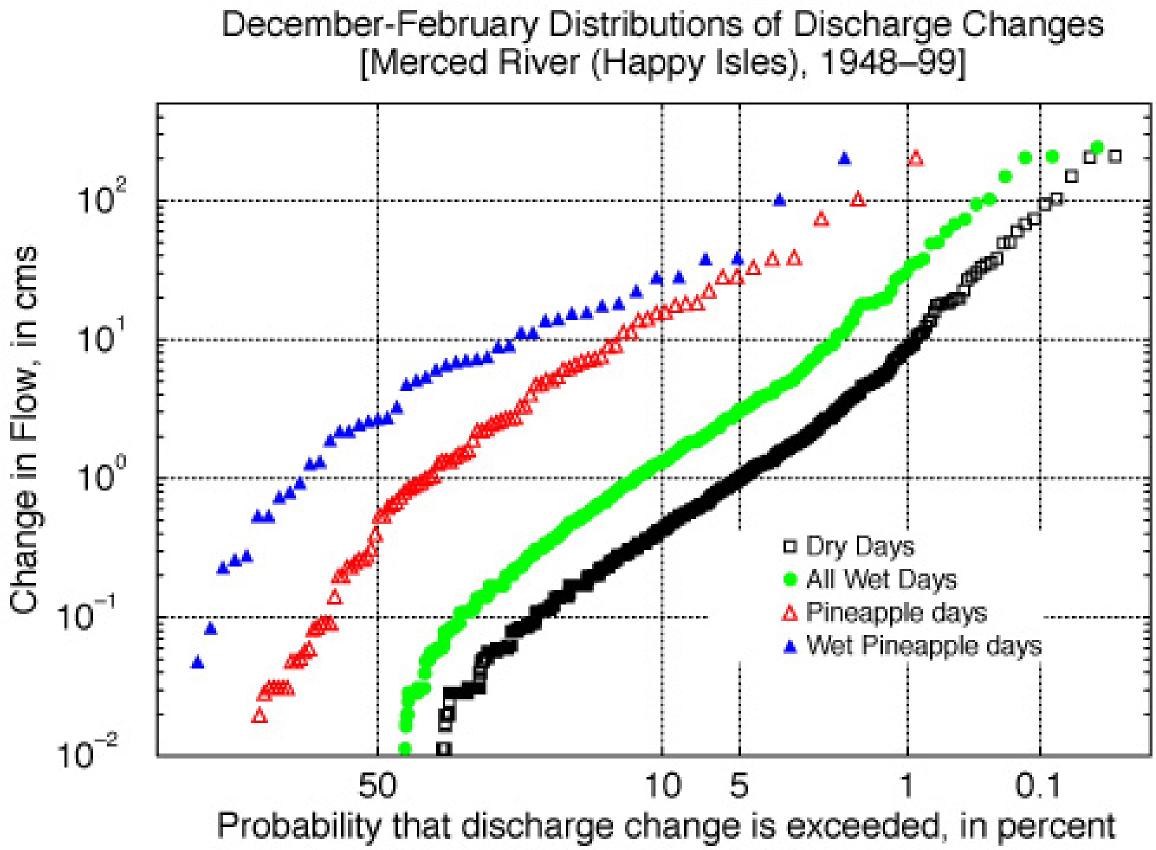


Figure 8. Exceedance probabilities for day-to-day changes in December–February discharges in the Merced River at Happy Isles, Yosemite National Park, under various circulation and precipitation conditions.

5. Summary

Pineapple-express circulations yield warm-wet storms along the west coast of North America, and are known for the floods that they can generate. This study analyzed daily water-vapor transport pathways from the NCEP Reanalysis to identify the occurrence of these circulations throughout the 52-year period from 1948 to1999, independently of whether the days were actually warm or wet on the West Coast. This approach identified 206 days on which large-scale atmospheric circulations were symptomatic of the pineapple-express condition. These days all occurred between October and April, most often in January and February. The water-vapor transports crossed the West Coast anywhere from 32ºN to 52ºN, with a modest maximum near 45ºN. The circulations have been most pronounced during winters when the PDO is in its positive, El Niño-like phase with ENSO in neutral or near-neutral conditions. The circulations yield storms over the West Coast states (and into Nevada and Idaho) and warm conditions over most of the western states. In the Sierra Nevada during winter, the storms average about twice as much precipitation as other, non-pineapple-express storms, yield warmer minimum temperatures, and produce daily increases in streamflow that are an order of magnitude larger than those from other types of storms.

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